

Networks of Economic Market Interdependence and Systemic Risk

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The dynamic network of relationships among corporations underlies cascading economic failures including the current economic crisis, and can be inferred from correlations in market value fluctuations. We analyze the time dependence of the network of correlations to reveal the changing relationships among the financial, technology, and basic materials sectors with rising and falling markets and resource constraints. The financial sector links otherwise weakly coupled economic sectors, particularly during economic declines. Such links increase economic risk and the extent of cascading failures. Our results suggest that firewalls between financial services for different sectors would reduce systemic risk without hampering economic growth.

The global economy is a highly complex system [1] whose dynamics reflects the connections among its multiple components, as found in other networked systems [2–4]. A common property of complex systems is the risk of cascading failures, where a failure of one node causes similar failures in linked nodes that propagate throughout the system, creating large scale collective failures. Economic risks associated with cascading financial losses are manifest in the current economic crisis [5] and the earlier Asian economic crisis [6], but are not considered in conventional measures of investment risk [7].

A central question is the role that complex systems science can play in informing regulatory policy that preserves the ability of markets to promote economic growth through freedom of investment, while protecting the public interest by preventing financial meltdowns due to systemic risk.

Characterizing the network of economic dependencies and its relationship to risk is key [8–12]. The dependencies among organizations involve large numbers of factors, including

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competition for capital and labor, supply and demand relationships among organizations that deliver common end products or rely upon common inputs, natural disasters and climate conditions, acts of war and peace, changes of government or its policies including economic policy such as interest rates, and geographic association. Quantifying such dependencies, *e.g.*, through Leontief models [13, 14], is difficult because many of the dependencies are non-linear and driven by socio-economic events not included in these models. Also, behavioral economics [15–17] suggests that under some conditions collective investor behavior, *e.g.*, from perceptions of value, may have significant effects. Reflecting both fundamental and behavioral interactions, correlations in market value of firms can serve as a measure of the perceived aggregate financial dependence and quantify “herding” behavior in collective fluctuations. Moreover, price correlations are directly relevant to measures of risk.

We constructed a network of dependencies among 500 corporations having the largest stock trading volume, augmented with several economic indices (oil prices, and bond prices reflecting interest rates). We formed a network where links are present for the highest correlations in daily returns in each year from 2003 to 2008. In order to display the effect of changes over time, we constructed a single network over all years, with each corporation in a particular year represented by a node linked to itself in the previous and next year. Each year is separately shown in Figure 1. We included only economic sectors that are significantly self-correlated, as the larger network constructed from the entire market obscures key insights. Previous correlational analyses have described how correlations may arise from external forces across the market (arbitrage pricing theory [18, 19]) or used correlations to characterize sectors and market crashes (econophysics [20, 21]). This work lacks an understanding of the economic origins of changes in dependencies and their policy implications. We examine variations of within- and between-sector correlations, arising from non-linear effects, for information about changes in economic conditions prior to and during the economic crisis.

The study of network community properties often requires careful analysis [22]. In our case, the observations we describe are manifest visually and were also tested statistically. In particular, apparent trends were tested using the t -statistic of differences in link densities within and between sectors (merging), or the minimum of this statistic between one sector and each of the others (self-clustering). Sectors are statistically linked (unlinked) to an index, if the t -statistic comparing links to the index relative to the link density of the graph is above 4 (below 2).

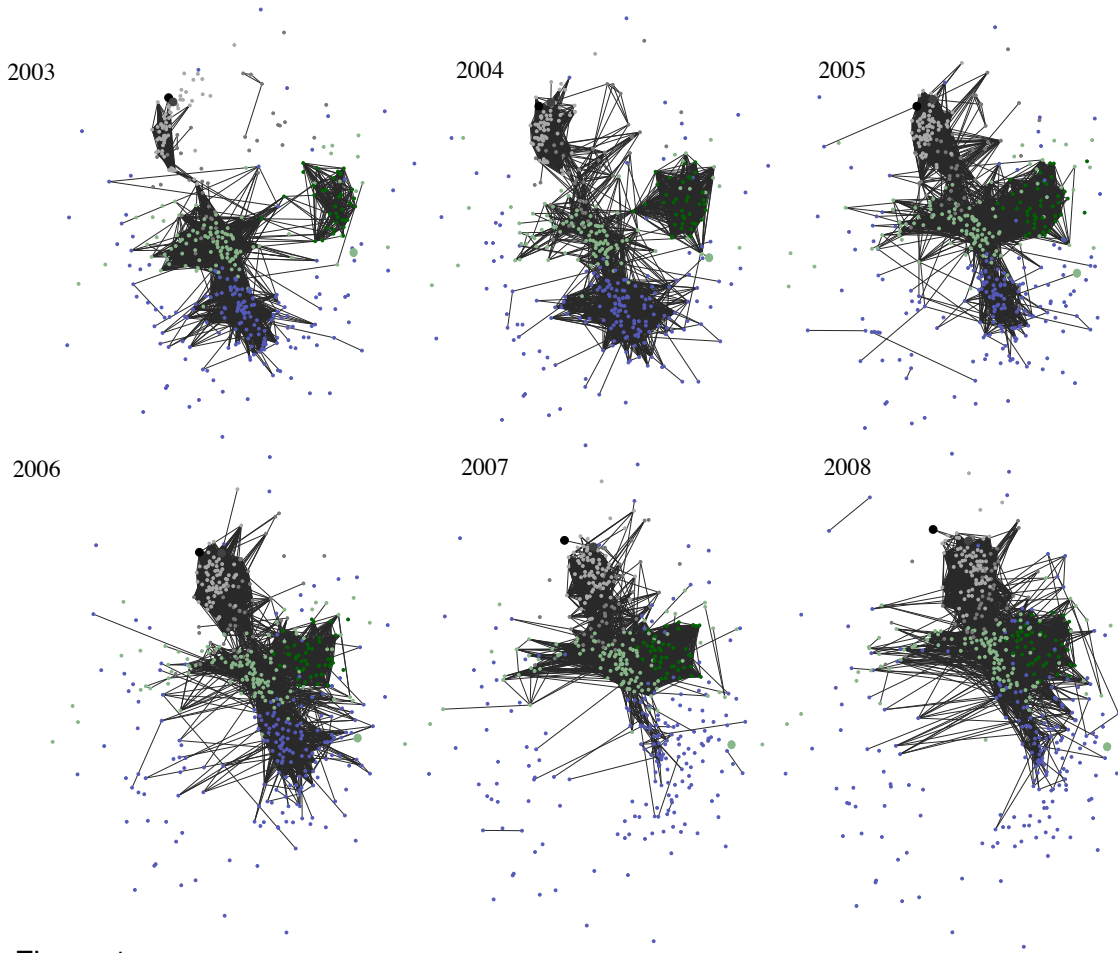


Figure 1

FIG. 1: Network of correlations of market daily returns for years as indicated. Dots represent individual corporations colored according to economic sector: technology (blue), basic materials including oil companies (light grey) and others (dark grey), and finance including real-estate (dark green) and other (light green). Links shown are the highest 6.25% of Pearson correlations of $\log(p(t)/p(t-1))$ time series, where $p(t)$ are adjusted daily closing prices of firms [50], in each year. Larger dots are spot oil prices at Brent, UK and Cushing, OK (black) and the price of ten year treasury bonds (green).

The following observations and trends from 2003 through 2008 are apparent and quantifiable: In 2003 there is a separate cluster of real estate related financial institutions (dark green), which over time merges into the larger financial cluster (green) (not merged through 2004 quarter 4, $p < 10^{-10}$, from 2007 quarter 2 to 2008 quarter 3, $p \geq 0.18$). The technology sector (blue), while strongly clustered during economic growth (2003-2006), becomes relatively weakly clustered during the economic crisis (2008) (self-clustering statistic has negative slope, $p < 10^{-66}$, and changes sign in 2008, $p < 10^{-10}$). Interest rates (larger green dot) are sometimes related to the technology cluster (linked for 8 out of 26 quarters). The

oil sector (grey) is highly clustered (any other sector is separate, $p < 10^{-13}$), and over time becomes increasingly linked to the rest of the basic materials cluster (dark grey) (positive slope, $p < 10^{-45}$), which itself becomes more connected to the technology cluster (positive slope, $p < 10^{-64}$). The oil cluster is only sometimes correlated to oil prices (large black dots) (linked for 7 of 27 quarters). We will show that the network dynamics are consistent with the sequence of economic events of the financial crisis [5]. In traditional external factor models and models of collective behavior in interacting systems [1], correlations are constant over time, but recent models have introduced the fitting of dynamical correlations of market indices [26, 27]. We will show that changes in correlations among corporations can be understood using intuitive models for this period of time.

Specific external events can be identified whose timing coincides with observed changes in correlations. Fig. 2C shows that the merger of the real estate and other financial sectors stocks coincides with both a peak in search frequency for “housing bubble” on Google [33], and a turning point in the behavior of housing prices ($p < 10^{-3}$). This timing is consistent with the understanding [5] that the decline in housing prices triggered the financial system crisis due to large investments in mortgage backed securities across the financial sector. Fig. 2D shows a potential role of critical resources: first, in the changing coupling of the basic materials sector to other parts of the economy; second, in the changing coupling of oil sector to oil prices, which is only one of the factors affecting the oil industry. Nonlinearity due to dramatic increases in prices can readily be explained because they are additive components of fundamental economic factors, *i.e.*, costs of production. When commodity prices are low, other components dominate, but when commodity prices are high they have larger effects, so the fractional variation is nonlinearly related to the total. The proximate coincidence of the severe commodities price increases [34] with the housing crisis ($p < 10^{-5}$) may be understood either through fears of commodity shortages due to rapid growth, or the transfer of investment from the housing sector to commodities [35]—investment demand rather than a use demand surge. This is consistent with the observation that economic growth by itself does not cause high correlations. However, general considerations of the role of constraints imply that when growth encounters the limit of available resources, increased correlations should occur as changes in one sector impact resource availability for another. Note that the correlations are primarily positive—commodity values rise with increasing financial sector values—consistent with fears of growth causing shortages or increasing investment demand.

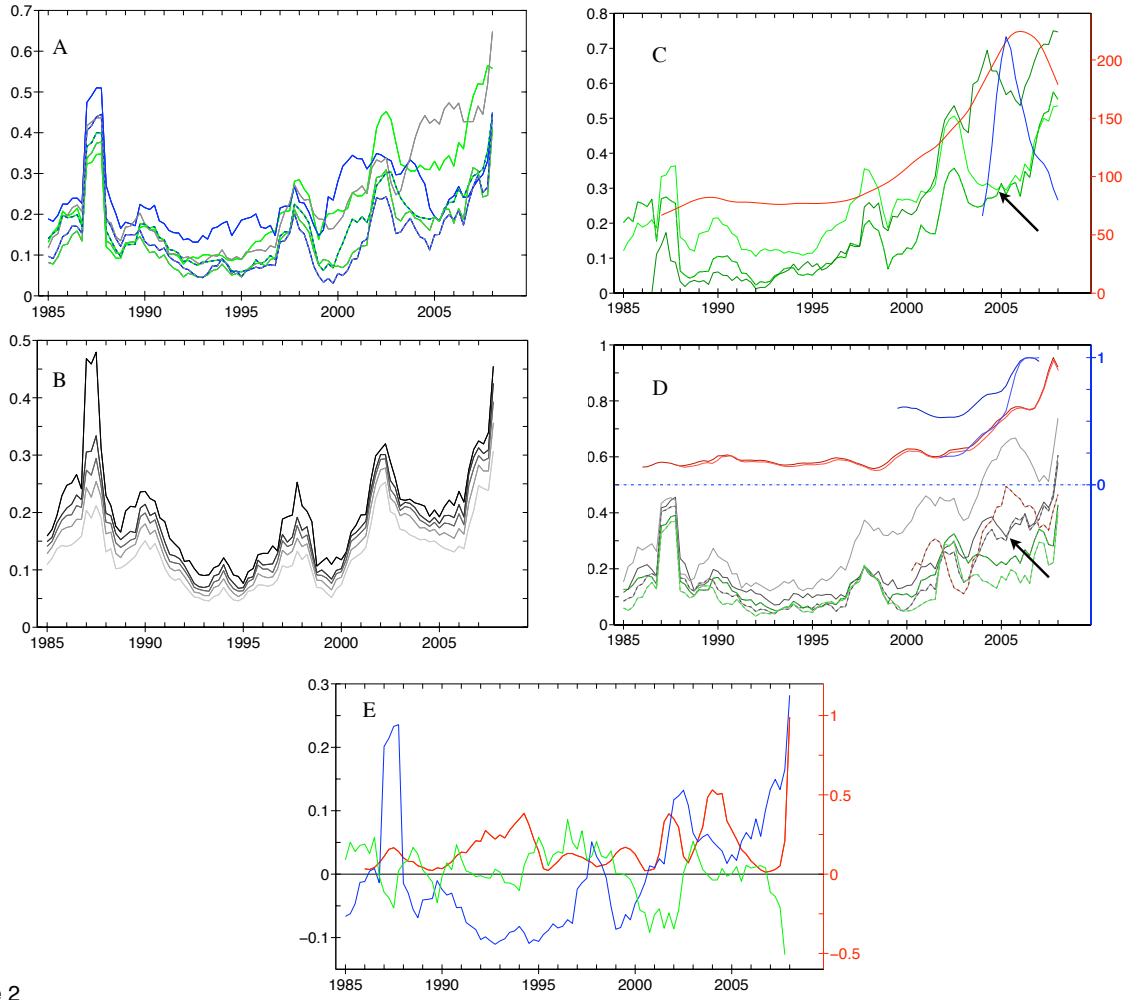


Figure 2

FIG. 2: Market correlations and external events from 1985 to 2008. **A:** The average strength of correlations within and between economic sectors. Sectors included are finance (green), technology (blue), and basic materials (grey), double colored lines are correlations between sectors (blue-grey, blue-green, and grey-green). Correlations are calculated using twelve month windows, shifted quarterly from Jan 1985 through Jan 2008. **B:** Average correlations among stocks from all economic sectors. Black to light grey lines omit in each 12 month period the highest 0, 2, 5, 10, 20 absolute average return days respectively. **C:** Financial sector correlations separated into real estate related (dark green), other (light green), and between these sectors (hatched light and dark green) using left axis scale. The arrow indicates the effective merger of the sectors. Also shown are a housing price indicator (red, using right axis scale) [51] and the search volume on Google for “housing bubble” (blue, arbitrary units) [52]. **D:** Basic materials sector correlations separated into oil (light grey) and others (dark grey) as well as finance (green), with mixed color lines reflecting inter-sector correlations (left axis scale). Also shown are prices of spot oil in Brent, UK (light red) and Cushing, OK (dark red), aluminum (light blue) and copper (dark blue) normalized to maximum values (right axis, both oil prices are normalized to the maximum of Cushing, OK). Average correlation of oil price in OK with the oil sector is shown (red/grey hatched). Arrow is the merger of oil and other basic materials. **E:** Rolling average correlations of the sectors in A (blue, left axis scale) shown with market value change (green, left axis scale, the return of S&P500 index). Market declines (negative returns) coincide with higher than average market correlations ($p < 0.02$). Also shown are effective limits on interbank loans (red, right axis scale, the difference between the London Interbank Offered Rate (LIBOR) and the Federal Funds Overnight Rate (annualized) at the beginning of each quarter, divided by the latter), having high values in the current economic crisis.

Negative correlations would be expected if commodity prices actually constrained economic growth.

Limiting investments (*i.e.*, limiting capital-to-asset ratios) in order to moderate risk directly influences opportunities for growth. However, our results also point to a different strategy, which recognizes that financial institutions cross-link otherwise weakly correlated economic sectors. The key is that economic couplings among companies propagate the effect of failures. If economic entity G fails in a financial obligation to entity H, the impact on H may affect other entities J and K, that are linked to H, even if their activity has nothing to do with G. Conversely, while a small capital-to-asset ratio may be risky for a particular institution, if the investments are within a particular economic sector the failure of that institution is unlikely to cause economy wide repercussions. Thus, segregating financial relationships, particularly among activities that are not otherwise related, or are weakly related, reduces systemic risk.

The idea that separations between components of the financial sector contribute to economic stability was a key aspect of legislation to stabilize the American banking system after the market crash of 1929. The Glass–Steagall Act of 1933 [44, 47] separated investment banking from consumer (retail) banking to prevent the fluctuations from other parts of the economy affecting consumer banking. This Act was progressively eroded until its repeal in 1999 [45]. Other historical forms of separation imposed by law or by practice included the separation of savings and loan associations and insurance providers from commercial and investment banking, as well as geographic separation by state [44, 45]. While many effects contribute to correlations in economic activity [13, 46], nonlinearities associated with investment during market declines support the historical intuition that regulating these dependencies is more critical than regulating those arising from, *e.g.*, supply chains. One of the arguments in favor of deregulation was that banks, by investing in diverse sectors, would have greater stability [47]. Our analysis implies that the investment across economic sectors itself creates increased cross-linking of otherwise much more weakly coupled parts of the economy, causing dependencies that increase, rather than decrease, risk. Quite generally, separation prevents failure propagation and connections increase risks of global crises. Subdivision is a universal property of complex systems [1, 48]. An increase in separation of financial services is likely to entail costs, and the cost-benefit tradeoffs of imposing particular types of separation are yet to be determined.

In summary, complex systems science focuses on the role of interdependence, a key aspect of the dynamical behavior of economic crises as well as the evaluation of risks in both “normal” and rare conditions. We have analyzed the dynamics of correlational dependencies in rising and falling markets. The impact on the economic system of repeals of Depression-era government policies is becoming increasingly manifest through scientific analysis of the current economic crisis. Previous studies [49] showed that repeal of the “uptick rule” in 2007 reduced economic stability by reducing returns and increasing fluctuations of the securities market. This study suggests that erosion of the Glass–Steagall Act, the consolidation of banking functions, and cross sector investments eliminated “firewalls” that could have prevented the housing sector decline from triggering a wider financial and economic crisis.

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